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RESEARCH ARTICLE

High moisture corn stover pelleting in a flat die pellet mill fitted with a 6 mm die: physical properties and specific energy consumption

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Keywords

High moisture corn stover, pellet properties, pelleting, specific energy consumption

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Abstract

The quality and specific energy consumption (SEC) of the biomass pellets produced depend upon pelleting process conditions. The present study includes understanding the effect of feedstock moisture in the range of 28–38% (wet basis [w.b.]) and preheating in the range of 30–110°C at two die speeds of 40 and 60 Hz on the physical properties and SEC. A flat die pellet mill fitted with a 6 mm die was used in the present study. The physical properties of pellets such as moisture content, unit, bulk and tapped density, durability, and expansion ratio and SEC of the pelleting process are measured. The results indicate that the pellets produced have durability values in the range of 87–98%, and unit bulk and tapped density in the range of 670–1100, 375–575, and 420–620 kg/m^3. Increasing the feedstock moisture content from 33% to 38% (w.b) decreased the unit, bulk and tapped density by about 30–40%. Increasing feedstock moisture content increased the expansion ratio and decreased the density values. A higher feedstock moisture content of 38% (w.b.) and higher preheating temperature of 110°C resulted in lower density and a higher expansion ratio, which can be attributed to flash off of moisture as the material extrudes out of the die. The SEC was in the range of 75–275 kWh/ton. Higher feedstock moisture content of 38% (w.b.) and a lower die speed of 40 Hz increased the SEC, whereas lower to medium preheating temperature (30–70°C), medium feedstock moisture content of 33% (w.b.), and a higher die speed of 60 Hz minimized the SEC to <100 kWh/ton.

Introduction

Bulk density of the plant-based biomass is low (50–130 kg/m^3) and needs to be increased to 500–700 kg/m^3 to reduce transportation and logistics costs and increase the storage stability [1]. Some of the advantages of densification include improved bulk density by five to seven times compared to raw biomass, improved handling and conveyance efficiencies, uniform size and shape, meeting the specifications of supply systems, and improved biochemical conversion performance [1]. The most commonly used densification systems include pellet mill, briquette press, and screw extruder. The pellets made from pellet mill are the most widely produced densified product and are transported intercontinentally for bioenergy applications. For example, wood pellets made in Canada and the United States are mainly exported to Europe for cofiring applications [2]. The pellets, which are transported to other countries from Canada and the United States, have to meet the standards established by the European Committee for Standardization (CEN) [2]. In the United States, the Pellet Fuel Institute (PFI), has established standard to transport pellets within and outside the nation. Typical dimensions of pellets used for residential and commercial application are 6 mm in diameter and 11–17 mm in length [2].

Pellet mill process variables

The process variables (like die rotational speed, die geometry [length to diameter (L/D) ratio], preheating temperature), and feedstock variables (like moisture content and particle size) influence the pellet physical properties like density, durability, and specific energy consumption (SEC) [1]. Studies on the effect of the preheating temperature on the density of wheat straw briquettes indicated that temperatures up to 90°C increased the density, but further increasing to 110°C reduced it [3]. This effect depends on the biomass composition where a high temperature (>90°C) is favorable for biomass that is high in protein content [4]. The die dimensions, such as diameter and length, affect the amount of material that can be pelleted, the quality of the pelleted material, and the energy required for compression. In general, smaller die diameters and lower rotational speeds are desirable for fibrous material, whereas bigger dies and higher die speeds are desirable for a wet and sticky biomass. Increasing the length of the pellet die increases pelleting pressure, whereas increasing the diameter of the pellet die decreases pelleting pressure [5]. Tabil and Sokhansanj [6] found that a bigger pellet die accommodates higher feedstock moistures. Their results indicated that a 6.2 mm die could process alfalfa with a moisture range of 7.5–9.0%, where a 7.8 mm die could tolerate moisture up to 12%. Feedstock moisture content and particle size also have a significant impact on the binding properties and quality of the pellets produced. A number of studies have indicated that fine grinding of biomass up to 2 mm produces denser pellets and increases the throughput of the machine [1, 6, 7]. At the same time, smaller particles less than 2 mm can lead to jamming of the pellet die and affect production capacity. Tumuluru et al. [1] in their review on densification systems for producing commodity type products from biomass indicated that feedstock moisture content lowers glass-transition temperature, promotes solid-bridge formation, and increases contact surface area. Many researchers have worked on pelleting and briquetting of biomass by adjusting feedstock moisture content in the range of 7–23% (w.b.) [8–14]. Some of the recent research articles published in 2014 have reported on pelleting raw, chemically and thermally pretreated biomass at moisture content >23% (w.b.) [15–19]. Recent preliminary studies on pelleting ammonia fiber explosion (AFEX) pretreated corn stover and municipal solid waste (consisting of about 30% plastic and nearly 70% being paper and noncorrugated cardboard) at a moisture content of about 19% and 15–25% (w.b.) in the ring die pellet mill (Bliss Pioneer Pellet Mill [B35A-75]), Bliss Industries, LLC), indicated good quality pellets in terms of bulk density (672 and 544 kg/m^3) and durability (99.6% and 98.4%) can be produced [20].

Pellet physical properties and SEC

Knowledge of the biomass pellet physical properties and the process variables influencing them is essential for producing high quality fuel pellets, designing equipment for processing facilities, and optimizing the unit operations. Some key quality attributes of fuel pellets are moisture content, density, and durability [1]. Pellet moisture content is important for safe storage and transportation. A higher moisture content of >15% (w.b.) can lead to pellet breakage as well as spoilage due to microbial decomposition, whereas a low moisture content of <3% can result in physical disintegration and generate more fines [1, 2]. Both higher and lower pellet moisture content can result in revenue loss for the pellet manufacturers. Density is important from a storage and transportation standpoint. Higher density helps to transport higher volumes of material and also helps to reduce the storage footprint at the conversion facilities. The durability indicates the integrity of the pellets during storage and transportation [21]. This can also be defined as the ability of the pellets to withstand the abrasive, impact, and frictional resistances during handling, storage, and transportation. Expansion ratio is defined as the ratio of diameter of the pellet to the diameter of pellet die. Expansion ratio is inversely proportional to the density of the pellet, where lower expansion ratio results in higher density [22]. In the case of fuel pellets, the lower expansion ratio is more desirable as expanded products will have high porosity and can be more reactive to storage environments. SEC of pelleting varies with different processing parameters, such as temperature and pressure, feedstock constituents (moisture content, particle size, and distribution), and chemical composition (starch, protein, lignin fat, waxes, and other lignocellulosic components) [1, 23]. Pellet mill rollers exert a constant pressure contingent upon the design of the pellet mill. The L/D ratio of the die determines the compression pressure. This parameter greatly influences the pellet quality and SEC [1, 24]. In the process of pelleting, the loose biomass is initially precompressed and deformed. The precompressed biomass further enters the die and balances the die's frictional forces as it extrudes through it [25]. To have a steady state pellet production, the roller pressure should be higher than both the compression pressure and frictional resistances. High fictional resistances in the die result in unsteady state pellet production and can increase the SEC.

High moisture pelleting

Tumuluru [15] and Tumuluru et al. [26] have indicated that pelleting corn stover feedstock at a high moisture content and further drying of the high moisture pellets at lower temperature of about 70–80°C using a grain dryer can be cost and energy efficient. Yancey et al. [27] and Pirraglia et al. [28] analyzed the energy consumption of various unit operations in a pellet production process and concluded that biomass drying from an initial feedstock moisture content of 30% (w.b.) to final moisture content of 10% (w.b.) using a rotary dryer consumes about 65–70% of the energy in the pellet production process, whereas pelleting requires approximately 9–13% of the energy. Sakkampang and Wongwuttanasatian [29] indicated that drying of biomass is the major energy consumer of the briquetting process. Their studies indicated that drying of biomasses such as rice husk, sawdust, sugarcane bagasse, and sugarcane leaf took about 2.25 MJ/kg, whereas the energy consumption for briquetting process was in the range of 0.04–0.10 MJ/kg. Figure 1 indicates the energy consumption reported by Yancey et al. [27] for the various unit operations like stage-1 and stage-2 grinding, drying, and pelleting during a conventional pellet production process. Tumuluru et al. [26] conducted techno-economic analyses on conventional and high moisture pelleting and briquetting production processes and concluded that high moisture pelleting offers significant energy savings (>50%) compared to conventional pelleting and briquetting processes. The low drying temperature associated with the high moisture pellet production process results in reducing the fuel cost, and in turn, the greenhouse gas emissions.

Objective

A continuous pelleting system, like a flat die pellet mill is typically used to develop a process at a laboratory scale [1]. The data on the continuous pelleting system will be helpful in understanding the effect of process conditions on the quality attributes and energy consumption. Tumuluru et al. [1] in their review on different densification systems to produce commodity type product from biomass indicated that the operating principle of flat die and commercial scale ring die pellet mill are the same, which makes it easier to scale up the process to a commercial scale system. Not much literature is available on how herbaceous biomass, such as corn stover, behaves during pelleting at high feedstock moistures of >28% (w.b.) in a continuous pelleting system. The study conducted by Tumuluru [15] on pelleting high moisture corn stover in a laboratory scale, flat die pellet indicated that pellets with bulk density (>500 kg/m^3) and durability (>95%) can be produced using an 8 mm pellet die.

The diameter of the pellets used in Europe varies between 6 and 12 mm. The 6 mm diameter pellet is preferred by the residential and commercial market since it generates less dust [2] and fits to different boiler configurations for steam generation. Six millimeter pellets also have higher packing density compared to other bigger die pellets. A study conducted by Tumuluru [15] on high moisture corn stover was done using an 8 mm pellet die and did not include data on the SEC. In his studies, the data on expansion ratio, which is an important physical property when extruding high moisture feedstock through a narrow constricted pellet die hole, is not discussed. Many researchers have identified expansion ratio as a good index to understand the effects of high moisture, and preheating temperature on the density of the food and feed pellets [22, 30–33]. Tumuluru [15] study on pelleting of high moisture corn stover indicated that lower (40 Hz) and higher (60 Hz) die speed had significant impact on pellet properties like density and durability. The specific objective of the present research is to understand how feedstock moisture content in the range of 28–38% (w.b.) and preheating temperature of 30–110°C at two die rotational speeds (40 and 60 Hz) impact the quality attributes, such as pellet moisture content; unit, bulk and tapped density; durability; expansion ratio; and SEC of pellets produced in a flat die pellet mill fitted with a 6 mm die.

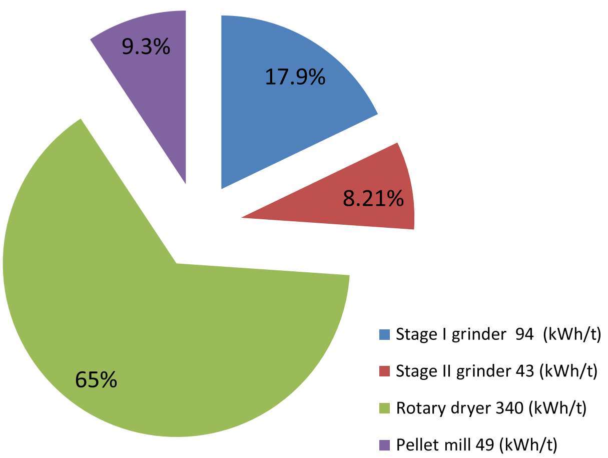

Figure 1. Energy consumption for the different unit operations for the pelleting of a lodgepole pine biomass.

Material and Methods

Feedstock

Harvested corn stover was procured from farms in Iowa in the form of bales and was initially ground to bigger particle sizes using a 50.8 mm screen with a Vermeer HG200 grinder (Vermeer Corporation-Agriculture, Pella, IA). The ground material was further reduced to smaller grinds (4.8 mm) using a hammer mill (Bliss Eliminator Hammer Mill, Model E-4424-TF) manufactured by Bliss Industries, Ponca City, OK [15, 27]. The ground material was evaluated for moisture content as well as bulk and tapped density using American Society of Agricultural and Biological Engineers (ASABE) standards [34]. The ground samples were further stored in airtight containers prior to pelleting tests.

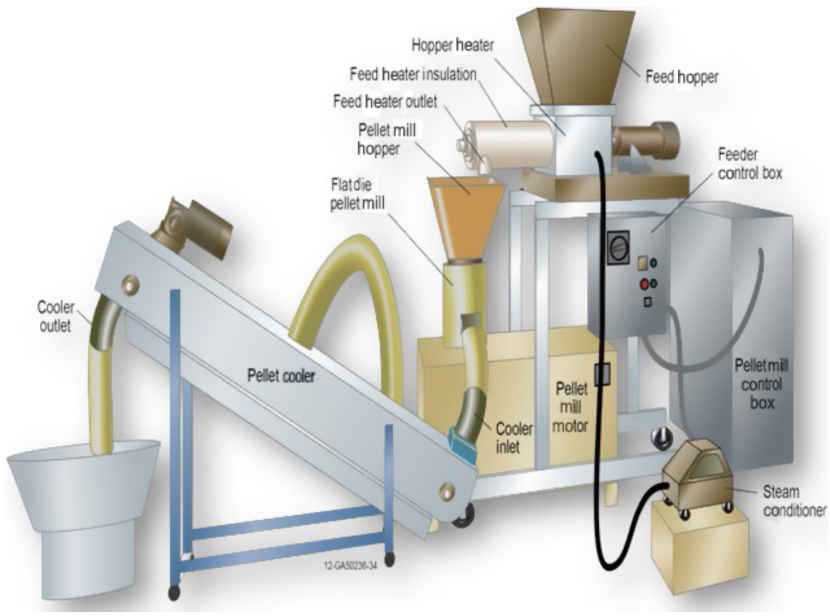

Figure 2. Flat-die pellet mill with other accessories (adapted from [15]).

Pelleting

A laboratory-scale ECO-10 (Colorado Mill Equipment, Canon City, CO, USA) flat-die pellet mill was used for the present studies (see Fig. 2). Tumuluru [15] has discussed in detail the pellet mill configuration. The pellet mill was equipped with a 10 HP, 460-V, three-phase motor. The hopper and screw feeder of the pellet mill were provided with flexible tape heaters, temperature controllers, and thermocouples to preheat the biomass to desired temperatures. A variable frequency drive (VFD) was provided to the pellet die to control the rotational speed and to the feeder to control the throughput rate. A horizontal pellet cooler was provided to cool the warm pellets coming out of the pellet die. Tumuluru [15] has discussed in detail the process for pelleting high moisture corn stover. About 2–3 kg of raw corn stover was mixed in a ribbon blender (RB 500, Colorado Mill Equipment, Canon City, CO, USA) with a calculated quantity of water to adjust moisture content to desired levels (28%, 33%, and 38%, w.b.). Experiments were conducted at different process conditions as indicated in Table 1. The moisture-adjusted corn stover was stored overnight in a refrigerator set at 4–5°C to equilibrate. This material was further loaded to the feed hopper of the pellet mill where it was preheated to different temperatures for short times (≈2–4 min) prior to pelleting. The feeding was carried out uniformly to assure there were no flow irregularities inside the pelletizer and to maintain a steady-state output. The pellets produced after cooling still had high moisture and were further dried in a mechanical oven at 70°C for about 3 h to reduce moisture content to <9% (w.b.). This makes pellets storable without any degradation. The dried pellets were further analyzed for physical properties like unit, bulk and tapped density; durability; and expansion ratio. The mill was provided with a power meter (Model no: APT-48T-MV-220-420; NK Technologies, San Jose, CA, USA). The percent motor power, pellet mill motor current, voltage, and die speed data were logged into a computer using LabVIEW software (Austin, TX, USA). Further, the percent motor power data collected for different experimental runs (Table 1) were used to calculate the power (kW) consumption.

Table 1. Experiments conducted at 40 and 60 Hz die speed at different feedstock moistures and preheating temperatures.

Experiment no.	Process variables	
	Feedstock moisture content (w.b.) (x_1)	Preheating temperature (°C) (x_2)
1	28	30
2	33	30
3	38	30
4	28	70
5	33	70
6	38	70
7	28	110
8	33	110
9	38	110

Physical properties

ASABE standards [34] were used to measure moisture content and bulk and tapped densities of moisture adjusted corn stover. The same standard was used to measure the pellets physical properties like unit, bulk, tapped density and durability. Brief descriptions of the methods followed are discussed below.

Moisture content

About 25–50 g of raw and pelleted corn stover samples were dried in a convective oven at 105°C for 24 h [34]. The samples were weighed before and after drying, and moisture content was calculated based on the change in weight. The values reported are in wet basis (w.b.) and are an average of three measurements.

Unit density

Unit density was measured to determine the density of individual pellets. The two ends of the pellets were made smooth with sandpaper. A vernier caliper was used to measure length and diameter of the pellet, and mass of the pellet was measured by using a balance with a 0.01 g precession [34]. Unit density was calculated by dividing the mass of an individual pellet by its volume. The reported values are an average of 10 pellets randomly selected from each experimental run.

Bulk and tapped density

The bulk density of the pellets produced was determined using a cylinder with a height to diameter (H/D) ratio based on ASABE Standard S269.4 [34]. Pellets were poured into the cylindrical container until they overflowed, and the surface of the cylinder was leveled by striking a straight edge across the top. The weight of the material and the cylinder volume were recorded. In case of tapped density, the loosely filled cylinder was tapped on a bench approximately five times, and the cylinder was again filled with pellets and leveled by striking the top. The reported values are an average of four measurements.

Durability

A pellet durability tester (Seedburo Equipment Co., Des Plaines, IL) with four compartments was used to measure the durability of the pellets. Fines were removed from pellets by sieving, and about 500 g of each sample was placed in each compartment of the tumbler. After tumbling at 50 rev/min for 10 min, the sample was removed and sieved using a 4.7 mm screen [34]. Pellet durability is defined as the ratio of weight of the tumbled sample after sieving to the total weight of the sample used for testing. The reported values are an average of four measurements.

Expansion ratio

The expansion ratio was calculated by using the pellet diameter data collected for the unit density measurement. The diametrical expansion ratio was calculated using the below equation [22].

$$ER = \frac{D^2}{d^2}, \tag{1}$$

where D is the diameter of the pellet extruded (mm) and d is the diameter of the die (mm). The reported values are an average of 10 measurements.

Specific energy consumption (SEC)

In the present study, the SEC for the pelleting process was calculated. For each pellet mill run, the percent motor data were logged using LabVIEW software. The percent motor power data were further converted to power (kW) based on Equation (2). This equation was provided by the power meter vendor. The size of the pellet mill motor is 10 HP, and approximate power loss due to VFD is about 114 W. Also, the vendor has indicated approximately 15% variability in the power (kW) consumption calculated using the percent motor power data.

$$\text{Power (kW)} = \frac{\left(\frac{\%\text{motor power}}{100}\right) \times (\text{Normal size of the motor horsepower}) \times (746\ \text{Watts/horsepower}) + (114)}{1000}. \tag{2}$$

The no-load power (kW) data of the pellet mill were recorded by running the pellet mill empty at 40 and 60 Hz die speed. This allowed determination of the net power required to pelletize the biomass material for each experimental run. SEC was calculated using the following formula: (eq. 3).

$$\text{SEC} = \frac{(\text{Full load Power (kW) - No load power (kW)}) \times \text{time (hr)}}{\text{weight of material (kg)}} \times 1000 = \frac{\text{kWh}}{\text{ton}}. \tag{3}$$

Results and Discussion

Initial raw material properties

The average moisture content of the raw materials was about 8.39% (w.b.), while the measured bulk and tapped densities were about 111 and 139 kg/m^3, respectively. Increasing the moisture of the corn stover to 28–38% (w.b.) brought a slight increase in bulk and tapped density by about 10–20 kg/m^3.

Pellet moisture content (%, w.b.)

Figure 3 indicates the effect of feedstock moisture content, die speed, and preheating on the pellet moisture content. Results indicated that moisture content of feedstock was reduced by about 5–10% (w.b.) after pelleting and cooling. The resulting pellets had moisture contents in the range of about 20–28% (w.b.). The present pellet moisture results have corroborated with earlier work on pelleting high moisture corn stover using an 8 mm pellet die [15]. At a feedstock moisture content of 28% (w.b.), die speed of 40 Hz, and preheating temperature of 110°C, the pellet moisture content observed was 21.29% (w.b.). By increasing the die speed to 60 Hz, the change in pellet moisture content was marginal (20.19% [w.b.]). At a higher feedstock moisture content of 38% (w.b.) and preheating temperature of 110°C, the pellet moisture observed was 27.97% (w.b.). The decrease in feedstock moisture content by about 10% (w.b.) when pelletized and cooled can be due to frictional heat developed in the pellet die, which can result in moisture flash off as the pellet is extruded. Further cooling of these pellets in a pellet cooler has also helped to remove some of the surface moisture. The present results have corroborated with our earlier research on pelleting of high moisture corn stover using an 8 mm pellet mill die [15], where feedstock moisture content influenced the final pellet moisture content of the pellets, and lower feedstock moisture content and higher preheating temperatures lowered the final pellet moisture content. A pilot scale pelleting study conducted on AFEX pretreated corn stover at about 19% (w.b.) moisture content using a ring die pellet mill (1 ton/h) indicated a decrease of about 9–10% (w.b.) feedstock moisture after pelleting [20]. The final moisture content of the AFEX pellets was found in-between 9% and 10% (w.b). Tumuluru et al. [1], in their review on biomass densification, indicated that moisture in the biomass feedstock helps in solid bridge formation by van der Waals forces and also lower the glass-transition temperature of some of the biomass components like lignin, protein and starch, which further takes an active part in the binding process. Furthermore, the presence of moisture, temperature and pressure in the pellet die enables some of the water soluble carbohydrates in the biomass to get solubilized and act as natural binder. The other biomass components which will be activated by moisture and temperature during the pelleting process are protein (which undergoes unfolding and denaturation) and starch

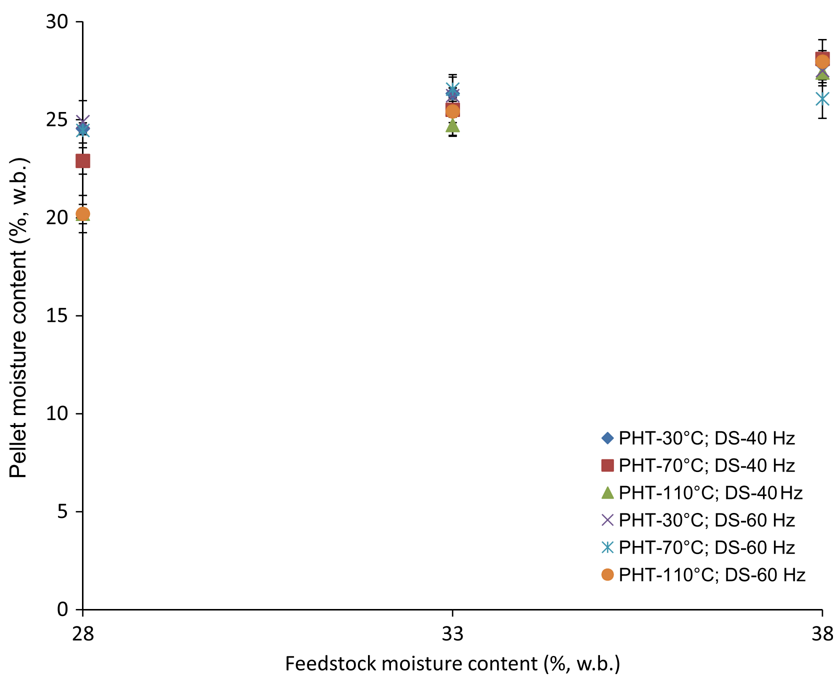

Figure 3. Effect of preheating, die speed, and feedstock moisture content on pellet moisture content.

(gelatinization) which result in formation of protein starch complexes.

Unit, bulk and tapped density (kg/m^3)

The highest unit density recorded was 1065 kg/m^3 at a lower moisture content of 28% (w.b.) with higher die speeds of 60 Hz, whereas bulk and tapped density values were 554 and 611 kg/m^3. Figures 4–6 indicate changes in unit, bulk and tapped densities with respect to preheating, die speed, and feedstock moisture content. Lower (28%, w.b.) and medium (33%, w.b.) feedstock moisture content and higher die rotational speed (60 Hz) maximized these properties. Typical unit densities of biomass pellets can be as high as 1100–1300 kg/m^3, and bulk densities are about 700 kg/m^3 [1, 2]. In their studies on pelleting of distillers dried grains with solubles, Tumuluru et al. [10] concluded that both unit and bulk densities of pellets made from the distillers dried grains are dependent on feed moisture and die temperature, where a maximum unit density of 1200 kg/m^3 and bulk density of 700 kg/m^3 is achievable at die temperature of about 100°C and feed moisture content of about >5%. Hall and Hall [35], in their studies of densification of Bermuda grass, indicated that moisture, pressure, and temperature influence density. They concluded the upper limits of the moisture content at which a certain pressure was able to produce a certain density also increased by preheating the biomass. Briquetting studies on *Caragana korshinskii* Kom biomass by Zhang and Guo [36] indicated that increasing the moisture content from 5–17% (w.b.) decreased the density. They found that moisture content is the most significant variable influencing the density. In the present study, it has been found that at a feedstock moisture content of 38% (w.b.) there is about 30–40% reduction in unit, bulk and tapped density compared to pellets made at 28% and 33% (w.b.) moisture content. Pelleting studies conducted by Mani et al. [37] on four biomass grinds such as wheat and barley straws, corn stover, and switchgrass at different moisture contents of 5, 10, and 15% (w.b.), indicated that pellets made at 5% (w.b.) had higher unit density as compared to pellets made at 15% (w.b.). This trend has corroborated with the present results where a lower feedstock moisture content of 28% (w.b.) resulted in higher unit, bulk and tapped density. Similar observations were reported by Rehkugar and Buchele [38] in their studies on forage wafers. They found that increasing the moisture content to 25% (w.b.) reduced the density. Pilot scale pelleting studies on AFEX pretreated corn stover at 19% (w.b.) moisture content resulted in bulk density of about 672 kg/m^3, whereas pelleting municipal solid waste (consisting of 30% plastic and about 70% paper and non-corrugated cardboard) at 15–25% (w.b.) moisture content produced pellets with density value of 544 kg/m^3 [20]. Both laboratory and pilot scale pelleting and briquetting indicated that the density of pellets or briquettes decreases with increase in feedstock moisture content. The possible explanation for lower bulk density at higher feedstock moisture content can be due to volumetric expansion of the pellet or briquettes due to moisture flash-off as it exits the die. Tumuluru et al. [13], in their studies on briquetting of wheat, oat, barley, and canola straws, indi-

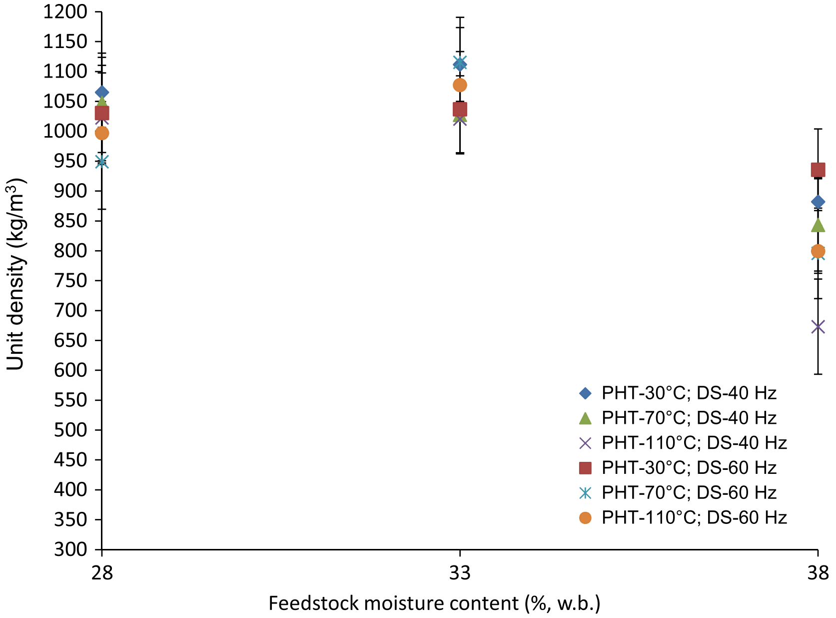

Figure 4. Effect of die speed, preheating, and feedstock moisture content on unit density.

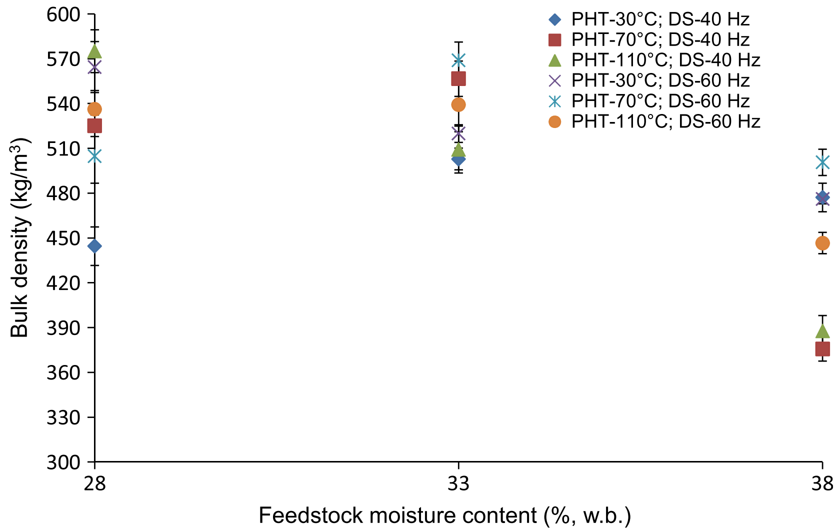

Figure 5. Effect of die speed, preheating, and feedstock moisture content on bulk density.

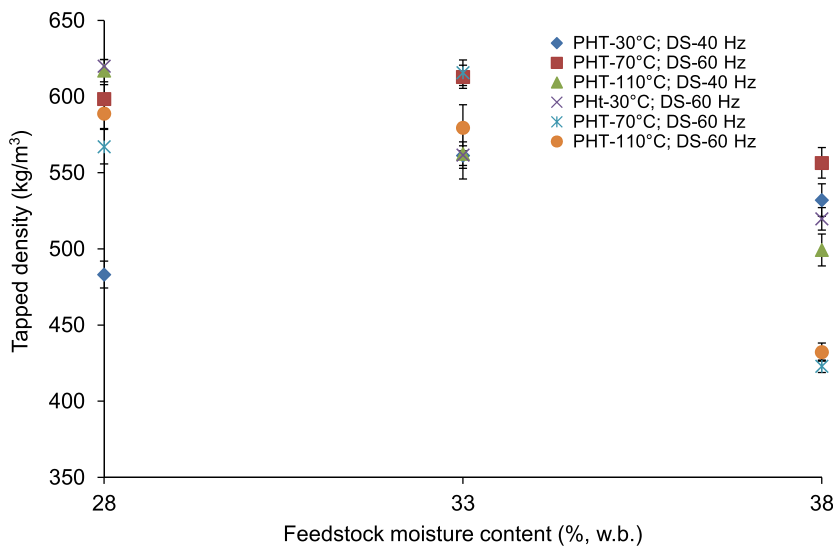

Figure 6. Effect of die speed, preheating, and feedstock moisture content on tapped density.

cated that increasing the moisture content to 15% (w.b.) and briquetting temperature to 130°C resulted in lower unit density. They reasoned that at higher feedstock moisture contents dimensional instability is higher for briquettes in both lateral and axial directions. In some cases, dimensional instability tends to be very marginal depending on the combination of the material and operating variables. A similar expansion trend was also reported by Mani et al. [39] on the compaction of corn stover and by Al-Widyan et al. [40] on the stability of olive cake briquettes.

Durability (%)

Durability values indicate the impact and shear resistances biomass pellets can withstand during transportation. Durability is one of the mandatory standards for pellets based on the Pellet Fuel Institute (PFI), USA and the European Committee for Standardization (CEN) [1, 2]. Pellets for international transport are expected to have durability values >97.5%, to retain the pellet integrity during long distance transportation. If pellets have lower durability values they can break and result in dust genera-

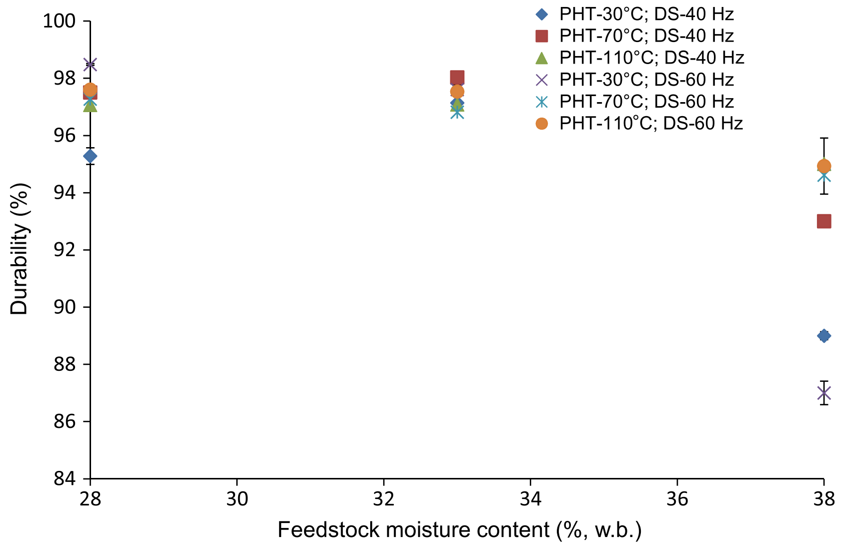

Figure 7. Effect of preheating, die speed, and feedstock moisture content on pellet durability.

tion which can lead to safety issues like spontaneous combustion, higher storage off-gas emissions, and revenue loss for the pellet producers. Figure 7 shows the plot drawn for durability values of pellets produced at different experimental conditions. From this figure, it is clear that feedstock moisture content of 28 and 33% (w.b.), and preheating temperatures of 70 and 110°C increased the durability values >95% (w.b.). Castellano et al. [41] observed that higher power and die temperatures increased durability values. In the present study, higher durability values of >95% observed can be due to the lowering of the glass-transition temperature of lignin and the increase in water soluble carbohydrates, which might have acted as natural binders during the pelleting process. Increasing the feedstock moisture content to 38% (w.b.) reduced the durability values to <90% at both 40 and 60 Hz die speeds. According to Koullas and Koukios [42], water in wheat straw helps in binding to make more durable briquettes. However, if the moisture content in the biomass feedstock crosses a threshold value, it acts more like a lubricant and results in less binding and more fines generation during the pellet or briquette production process. Kaliyan and Morey [21, 43] suggested that the binding of biomass during densification is strongly affected by the glass-transition temperature of lignin, which in turn is dependent on moisture content and preheating temperatures. Zhang and Guo [36], Tumuluru et al. [13], and Tumuluru [15] have found that the durability of *C. korshinskii* Kom and agricultural straw biomass briquettes and pellets made from high moisture corn stover has increased with an increase in the preheating temperature. This result has corroborated with present findings where higher preheating temperature of >70°C resulted in higher durability pellets.

Expansion ratio

The measurement of the expansion ratio helps to understand the diametrical expansion of the extruded biomass pellets. Figure 8 indicates the effects of feedstock moisture content and preheating temperature on the expansion ratio. Expansion ratio of the biomass pellets made from low moisture (10–12%, w.b.) feedstock using conventional pelleting process is typically ≤1.0. In the present study, increasing the feedstock moisture content to 38% (w.b.) and preheating temperatures to 110°C increased the expansion ratio of pellets to >1.26, whereas at a lower feedstock moisture content of 28% (w.b.), a minimum expansion ratio of <1.06 was observed. The results also indicated that the expansion ratio values did not change much by increasing the moisture content from 28% to 33% (w.b.). In general, lower expansion ratio values are preferred for fuel pellets as they result in higher densities. Poddar et al. [16] indicated that biomass pellets expanded after pelleting at higher feedstock moistures. They have reasoned that heat generated during pelleting, owing to friction between the biomass particles and prechannel of the die hole as well as the application of pressure, results in expelling of moisture as the pellet exits the die. Mohesenin and Zaske [44] and Faborode [45] indicated that high moisture in the feedstock makes briquettes expand, thereby resulting in higher residual stresses in the briquettes after ejection from the die, causing an elastic spring back or expansion. Kaliyan and Morey [43] indicated that an increase in feedstock moisture content subsequently increased the expansion of the briquettes at higher preheating temperatures. Figure 9 is drawn to understand the relationship between expansion ratio and

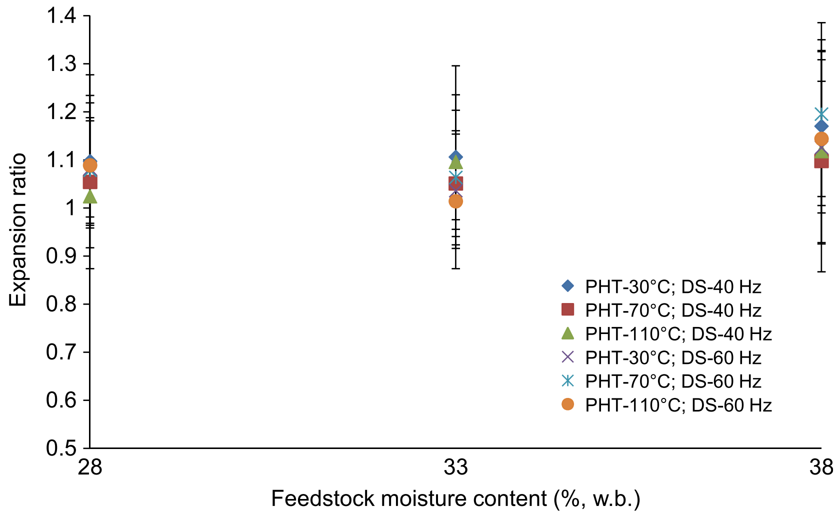

Figure 8. Effect of preheating, die speed, and feedstock moisture content on expansion ratio.

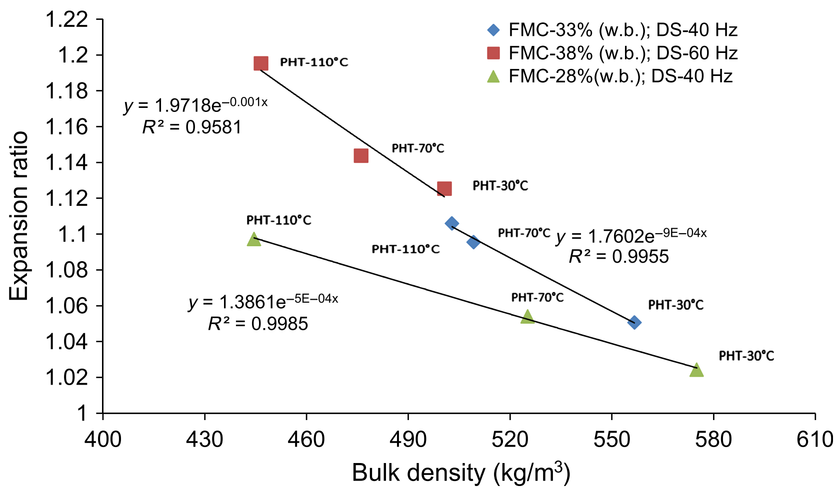

Figure 9. Effect of expansion ratio on bulk density at different die speed, preheating temperature and feedstock moisture content.

bulk density of the pellets produced. It is very clear from the figure that higher expansion ratio reduced the bulk density of the pellets. Higher feedstock moisture content led to a higher expansion ratio and, in turn, lowered the bulk density. The exponential equation fitted (Fig. 9) indicated that at lower feedstock moisture of 28% (w.b.), the expansion ratio is lower, whereas at a higher feedstock moisture content (38%, [w.b.]), expansion ratio is higher.

Specific energy consumption (SEC) (kWhr/ton)

In general, the SEC during pelleting is governed by feedstock moisture content, die dimensions, feedstock composition, feeding rate, and die rotational speed [1]. Higher die rotational speed can increase the throughput of the pellet mill and reduce the SEC. Figure 10 indicates the effect of preheating and feedstock moisture content on the SEC (kWh/ton). It is very clear from the plot that at feedstock moisture content of 33% (w.b.), and increasing the die speed to 60 Hz and preheating temperature to 70°C decreased the SEC to about 75 kWh/ton. At feedstock moisture content of 38% (w.b.), die speed of 40 Hz and preheating temperature of 70 and 110°C the SEC increased to about 275 kWh/ton. In the present study at higher feedstock moisture content of 38% (w.b.), slower feeding rates were used to produce more pellets and fewer fines. Lowering the feed rate at higher feedstock moisture has resulted in reduced throughput and increased the energy consumption. Also, die speed had a prominent effect on the throughput and in turn the SEC, where at

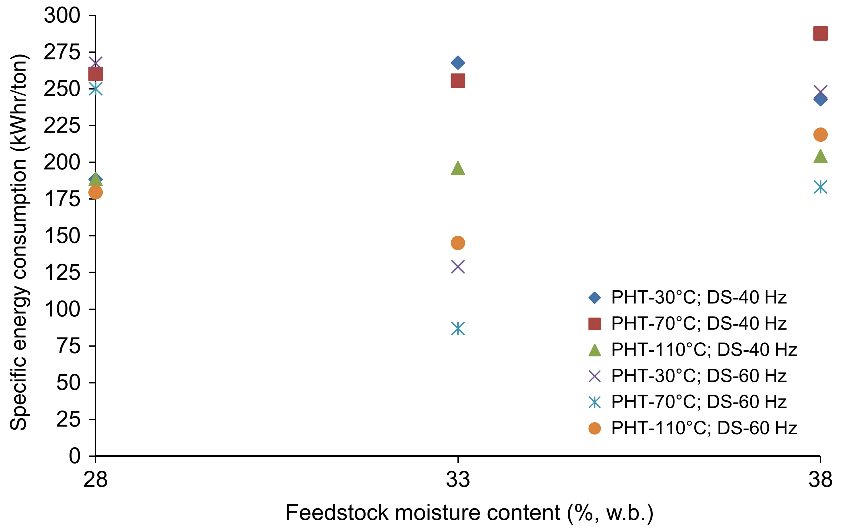

Figure 10. Effect of preheating, die speed, and feedstock moisture content on specific energy consumption.

40 Hz the observed SEC values were higher compared to 60 Hz. Reed et al. [23] indicated that increasing the preheating temperature reduces the SEC. According to Holm et al. [5], the length and diameter of the pellet die has a significant effect on the compression pressures. Increasing the length of the pellet die increases the pelleting pressure, whereas increasing the diameter decreases the pelleting pressure. So for the same L/D ratio, a bigger pellet die like 8 mm may need lower compression pressure, which might result in lowering the SEC compared to smaller die (≤6 mm).

Discussion

The current research results on density and durability for 6 mm pellets were compared with the 8 mm pellets produced by Tumuluru [16]. The densities of the pellets produced using a 6 mm die are slightly lower by about 20–30 kg/m^3 compared to an 8 mm die. This reduction in density can be due to a higher expansion of pellets as the high moisture biomass material exits through a smaller, constricted die size. High moisture biomass at temperatures >100°C, when passing through a constricted hole, results in moisture loss due to flash-off. Shankar and Bandyopadhyay [22] and other researchers have indicated that extruding high moisture (>30, w.b) food at a preheating temperature >100°C results in expansion of the extrudate due to flash-off of moisture as it leaves the die. The moisture flash-off from the extrudates can be higher when the die dimensions are smaller. In the case of durability for both 6 and 8 mm die corn stover pellets, pelleting at high moisture feedstock (28–38%, w.b.) resulted in durability values in the range of 85–96%. According to the Pellet Fuel Institute (PFI), USA, and the European Committee for Standardization (CEN), durability and bulk density are normative specification for grading of pellets [2]. Pellets with durability values >96.5% and bulk density >640 kg/m^3 are designated as super premium pellets based on PFI standards; whereas in the case of CEN the durability and bulk density values should be >97.5% and >700 kg/m^3 [2] for international transport. Both PFI and CEN have other density and durability standards for lower grade pellets [2]. In general to transport pellets for shorter distances (e.g., interstate), very high density and durability values may not be required. This gives an opportunity to customize the pellet production process to produce pellets with varying durability and density values to meet different transportation scenarios. The present study has indicated that pellets with different density and durability can be produced at different feedstock moistures, die speeds, and preheating temperatures and these process conditions have a significant impact on the pelleting energy. For both 6 and 8 mm die sizes, lower to medium moisture contents of 28–33% (w.b.) and preheating temperatures of about 70°C resulted in higher durability values of >90% and bulk density of >520 kg/m^3.

The present results indicated that pellets produced using high moisture corn stover (28–38%, w.b), has resulted in lower density (575–375 kg/m^3) compared to pellets produced using the same material at 10% (w.b.) moisture content using conventional or low moisture pelleting process (645 kg/m^3) [27]. The major reason for loss of pellet density at higher feedstock moisture content is due to diametrical expansion of the pellet as it exits the die. The expansion is a common phenomenon when extruding high-moisture feedstock. One way to reduce diametrical expansion of a pellet or briquette at higher feedstock moisture content is to add natural or commercial pellet binders. Tumuluru et al. [46] studies on extrusion of high-protein foods indicated that higher levels of proteins in the food mix can reduce the expansion and increase the hardness values of food pellets. The same authors indicated that the presence of higher amounts of starch in the biomass can increase the expansion ratio thereby reducing the density of the extrudates. Tumuluru et al. [13] in their studies found that canola straw which is high in protein content produced denser and more durable briquette compared to wheat, oat, and barley. They also found that the diametrical expansion or the spring back is lower in canola straws. Another important pellet mill parameter that has a great impact on the quality and energy consumption of the pelleting process is the L/D ratio of the pellet die. The L/D ratio controls the residence time of the material in the die and impact the quality attributes like density and durability. The L/D ratio also impacts the extrusion energy needed in the pelleting process. For the same die diameter, increasing the length of the pellet die increases the extrusion energy. Mewes [47] indicated that about 37–40% of the energy used during pelleting is needed to compress the biomass, whereas as the remaining energy of about 60–63% is needed to extrude the biomass out of the pellet die. Our further research is aimed at understanding the impact of binders and the L/D ratio of the pellet die on the pellet quality attributes (density and durability) and energy consumption of high moisture pelleting process.

Techno-economic analysis conducted by Tumuluru et al. [26] on conventional and high moisture pelleting indicated that there is a significant advantage in pelleting biomass at high moisture in terms of cost and energy. This process also enables the use of agricultural machinery like grain dryers which have lot of advantages compared to rotary dryers [15]. Low cost and energy-efficient dryers (such as grain or belt dryers) operate at low temperatures (60–80°C), and can be operated using low-quality heat. Low operating temperatures of the grain dryer helps to reduce the volatile organic compounds (VOC) emissions and can have a significant impact on the greenhouse gas emissions. The low drying temperatures associated with grain dryers will also reduce the risk associated with fire and explosion. Drying biomass pellets at a low temperature and for longer drying times also ensures that the product is dried more uniformly. Additionally, our studies are aimed at how the drying times impact the moisture distribution within the pellets and the quality of the pellets (density and durability).

Recently, chemical pretreatment methods like leaching, acid, alkali, and ammonia fiber explosion (AFEX) are gaining importance for both thermochemical and biochemical conversion applications [17, 48–51]. These pretreatments result in high moisture in the biomass feedstock, which need to be dried to a final moisture of <12% (w.b.) to increase their storage stability and for further pelleting or briquetting. Drying these chemically pretreated biomass materials, lowers the bulk density compared to their original state, which can be a major limitation to transport over longer distances. One way to reduce the preprocessing costs and overcome the low density limitation is by pelleting high moisture chemically pretreated biomass and further drying the high moisture pellets using a grain or belt dryer. This process helps to reduce the preprocessing costs, improve the storage stability, and increase the transportation efficiencies of chemically pretreated biomass. Our recent studies on pelleting the AFEX pretreated corn stover at 26% and 19% (w.b.) moisture content in a laboratory scale (flat die) and a pilot scale (ring die) pellet mill indicated that good quality pellets with high density (>600 kg/m^3) and durability (>98%) can be produced [17, 20].

Conclusions

The experimental data indicated that good quality pellets in terms of density and durability can be made using high moisture corn stover in a flat die pellet mill fitted with a 6 mm die. Different pelleting conditions resulted in the different quality of pellets as well as different SEC. Feedstock moisture content had a significant impact on the quality of the pellets. High moisture contents resulted in lower quality in terms of density and durability. Lower unit, bulk and tapped densities were observed at higher feedstock moisture contents, and the expansion ratios observed were higher. The present findings indicate that a higher expansion ratio results in lower bulk density. At 38% (w.b.) feedstock moisture content there was a decrease in bulk density by about 30–40% compared to pellets made at 28% and 33% (w.b.) feedstock moisture content. The high quality of pellets in terms of density and durability at lower SEC can be produced at feedstock moisture contents of 33% (w.b.), higher die speeds of 60 Hz, and low and medium preheating temperature of 30 and 70°C.

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References

1. Tumuluru, J. S., C. T. Wright, J. R. Hess, and K. L. Kenney. 2011. A review of biomass densification systems to develop uniform feedstock commodities for bioenergy application. Biofuel. Bioprod. Bior. 5:683–707.
2. Tumuluru, J. S., S. Sokhansanj, C. J. Lim, X. T. Bi, A. Lau, S. Melin, et al. 2010a. Quality of wood pellets produced in British Columbia for export. Appl. Eng. Agric. 26:1013–1020.
3. Smith, I. E., S. D. Probert, R. E. Stokes, and R. J. Hansford. 1977. The briquetting of wheat straw. J. Agr. Eng. Res. 22:105–111.
4. Tabil, L. G.. 1996. Binding and pelleting characteristics of alfalfa. Ph.D. diss., Department of Agricultural and Bioresource Engineering, University of Saskatchewan, Canada.
5. Holm, J. K., U. B. Henriksen, J. E. Hustad, and L. H. Sorensen. 2006. Toward an understanding of controlling parameters in softwood and hardwood pellets production. Energ. Fuels 20:2686–2694.
6. Tabil, L. G., and S. Sokhansanj, S. 1996. Process conditions affecting the physical quality of alfalfa pellets. Trans. ASAE. 12:345–350.
7. Dobie, J. B. 1959. Engineering appraisal of hay pelleting. Agr. Eng. 40:72–76.
8. Mani, S., L. G. Tabil, and S. Sokhansanj. 2006. Specific energy requirement for compacting corn stover. Bioresour. Technol. 97:1420–1426.
9. Li, Y., and H. Liu. 2000. High–pressure densification of wood residues to form an upgraded fuel. Biomass Bioenerg. 19:177–186.
10. Tumuluru, J. S., L. G. Tabil, A. Opoku, M. R. Mosqueda, and O. Fadeyi. 2010b. Effect of process variables on the quality characteristics of pelleted wheat distiller's dried grains with soluble. Biosyst. Eng. 105:466–475.
11. Tabil, L. G., and S. Sokhansanj. 1996. Compression and compaction behavior of alfalfa grinds, Part 1: compression behavior. Powder Handl. Proces. 8:17–23.
12. Ndiema, C. K. W., P. N. Manga, and C. R. Ruttoh. 2002. Influence of die pressure on relaxation characteristics of briquetted biomass. Energ. Convers. Manag. 43:2157–2161.
13. Tumuluru, J. S., L. G. Tabil, Y. Song, K. L. Iroba, and V. Meda. 2015. Impact of process conditions on the density and durability of wheat, oat, canola, and barley straw briquettes. Bioenerg. Res. 8:388–401.
14. Zafari, A., and M. H. Kianmehr. 2013. Factors affecting mechanical properties of biomass pellets from compost. Environ. Technol. 35:478–486.
15. Tumuluru, J. S. 2014. Effect of process variables on the density and durability of the pellets made from high moisture corn stover. Biosyst. Eng. 119:44–57.
16. Poddar, S., M. Kamruzzaman, S. M. A. Sujan, M. Hossain, M. S. Jamal, M. A. Gafur, et al. 2014. Effect of compression pressure on lignocellulosic biomass pellet to improve fuel properties: higher heating value. Fuel 131:43–48.
17. Hoover, A. N., J. S. Tumuluru, F. Teymouri, M. Moore, and G. Gresham. 2014. Effect of pelleting process variables on physical properties and sugar yields of ammonia fiber expansion (AFEX) pretreated corn stover. Bioresource Technol. 164:128–135.
18. Sarkar, M., A. Kumar, J. S. Tumuluru, K. N. Patil, and D. D. Bellmer. 2014a. Thermal devolatilization kinetics of switchgrass pretreated with torrefaction and densification. Trans. ASABE 57:1199–1210.
19. Sarkar, M., A. Kumar, J. S. Tumuluru, K. N. Patil, and D. D. Bellmer. 2014b. Gasification performance of switchgrass pretreated with torrefaction and densification. Appl. Energ. 127:194–201.
20. Pace, D. 2015. Pelleting of municipal solid wast and ammonia fiber explosion (AFEX) pretreated corn stover in a pilot scale ring die pellet mill. Biofuels Department, Chief Engineer, Biomass National User Facility, Idaho National Laboratory (Unpublished data).
21. Kaliyan, N., and R. V. Morey. 2009a. Factors affecting strength and durability of densified biomass products. Biomass Bioenerg. 33:337–359.

22. Shankar, T. J., and S. Bandyopadhyay. 2005. Process variables during single-screw extrusion of fish and rice-flour blends. J. Food Process. Pres. 29:151–164.
23. Reed, T. B., G. Trezek, and L. Diaz. 1980. Biomass densification energy requirements, Chapter 13. Pp. 169–177 *in* J. L. Jones, S. B. Radding, S. Takaoka, A. G. Buekens, M. Hiraoka, R. Overend, eds. Thermal conversion of solid wastes and biomass. American Chemical Society, Washington, DC. doi: 10.1021/bk-1980-0130
24. Stelte, W. 2011. Fuels pellets from biomass: processing, bonding, raw materials. Ph.D. thesis, National Laboratory for Sustainable Energy, Riso, Technical University of Denmark.
25. Winter, E. 1981. Fundamental considerations for preparing densified refuse derived fuel. U.S. Environmental Protection Agency, Technical Report EPA- 600/S2-81-180, Mun Env Res Lab, Cincinnati, OH.
26. Tumuluru, J. S., K. G. Cafferty, and K. L. Kenney. 2014. Techno-economic analysis of conventional, high moisture pelletization and briquetting process. American Society of Agricultural and Biological Engineer Annual Meeting, Paper No. 141911360, Montreal, Quebec Canada July 13 – 16, 2014, (doi: 10.13031/aim.20141911360).
27. Yancey, N. A., J. S. Tumuluru, and C. T. Wright. 2013. Drying, grinding and pelletization studies on raw and formulated biomass feedstock's for bioenergy applications. J. Biobased. Mater. Bioener. 7:549–558.
28. Pirraglia, A., R. Gonzalez, and D. Saloni. 2010. Technoeconomic analysis of wood pellets production from U.S. Manufactures. BioReosurces 5:2374–2390.
29. Sakkampang, C., and T. Wongwuttanasatian. 2014. Study ratio of energy consumption and gained energy during briquetting process for glycerin – biomass briquette fuel. Fuel 115:186–189.
30. Oke, M. O., S. O. Awonorin, and T. S. Workneh. 2013. Expansion ratio of extruded water yam (Dioscorea alata) starches using a single screw extruder. Afr. J. Agr. Res. 8:750–762.
31. Filli, K. B., I. Nkama, and V. A. Jideani. 2013. The effect of extrusion conditions on the physical and functional properties of millet-Bambara groundnut based fura. Am. J. Food Sci. Tech. 1:87–101.
32. Yuryey, V. P., D. V. Zasypkin, V. V. Alexeev, and A. N. Bogatyryev. 1995. Expansion ratio of extrudates prepared from potato starch-soybean protein mixtures. Carbohydr. Polym. 26:215–218.
33. Shankar, T. J., and S. Bandyopadhyay. 2004. Optimization of extrusion process variables using a genetic algorithm. Food Bioprod. Process. 82:143–150.
34. ASABE Standards. 2007. S269.4. Cubes, pellets, and crumbles – definitions and methods for determining density, durability, and moisture content. ASABE, St. Joseph, MO.
35. Hall, G. E., and C. W. Hall. 1968. Heated-die wafer formation of alfalfa and bermudagrass. Trans. ASAE 11:578–581.
36. Zhang, J., and Y. Guo. 2014. Physical properties of solid fuel briquettes made from *Caragana korshinskii* Kom. Powder Technol. 256:293–299.
37. Mani, S., L. G. Tabil and S. Sokhansanj. 2002. Compaction characteristics of some biomass grinds. AIC 2002 Meeting, CSAE/SCGR Program, Saskatoon, Saskatchewan, Canada, July 14–17, 2002.
38. Rehkugar, G. E., and W. F. Buchele. 1969. Bio-mechanics of forage wafering. Trans. ASAE 12:1–8.
39. Mani, S., L.G. Tabil, and S. Sokhansanj. 2004. Compaction of corn stover. ASAE Paper No 041160, presentation at the 2004 ASAE/CSAE Annual International Meeting.
40. Al-Widyan, M. I., H. F. Al-Jalil, M. M. Abu-Zreig, and N. H. Abu-Handeh. 2002. Physical durability and stability of olive cake briquettes. Can. Biosyst. Eng. 44:341–345.
41. Castellano, J. M., M. Gomez, M. Fernandez, L. S. Esteban, and J. E. Carrrasco. 2015. Study on the effects of raw materials composition and pelletization conditions on the quality and properties of pellets obtained from different woody and non woody biomasses. Fuel 139:629–636.
42. Koullas, D. P., and E. G. Koukios. 1987. Hot briquetting of wheat straw. Pp. 53–60 *in* P. Keller, ed. In Handling and processing of biomass for energy. Report and proceedings CNRE Bulletin (FAO), No. 18; European Cooperative Networks on Rural Energy. Workshop on Handling and Processing of Biomass for Energy, 1, Hamburg, Germany, F.R., 14–15 September 1987. FAO, Rome, Italy. Regional Office for Europe.
43. Kaliyan, N., and R. V. Morey. 2009b. Densification characteristics of corn stover and switchgrass. Trans. ASABE. 52:907–920.
44. Mohsenin, N., and J. Zaske. 1976. Stress relaxation and energy requirements in compaction of unconsolidated materials. J. Agr. Eng. Res. 11:193–205.
45. Faborode, M. O., and J. R. O. Callaghan. 1987. Optimizing the compression/briquetting of fibrous agricultural materials. J. Agr. Eng. Res. 38:245–262.
46. Tumuluru, J. S., S. Sokhansanj, S. Bandyopadhyay, and A. S. Bawa. 2013. Changes in moisture, protein and fat content of fish and rice flour coextrudates during single-screw extrusion cooking. Food Bioprocess Tech. 6:403–415.
47. Mewes, E. 1959. Berechung der druckverteilung an stroh- und heupressen [Calculation of the pressure distribution in straw and hay balers]. Landtechnische Forschung 9:160–170.
48. Balan, V., B. Bals, S. P. Chundawat, D. Marshall, and B. E. Dale. 2009. Lignocellulosic biomass pretreatment using AFEX. Methods Mol. Biol. 581:61–77.
49. Bals, B., C. Rogers, M. Jin, V. Balan, and B. E. Dale. 2010. Evaluation of ammonia fibre expansion (AFEX) pretreatment for enzymatic hydrolysis of switchgrass

harvested in different seasons and locations. Biotechnol. Biofuels 3:61–77.
50. Kumar, P., D. M. Barrett, M. J. Delwiche, and P. Stroeve. 2009. Methods for Pretreatment of Lignocellulosic Biomass for Efficient Hydrolysis and Biofuel Production. Ind. Eng. Chem. Res. 48:3713–3729.
51. Thompson, D. N., T. Campbell, B. Bals, T. Runge, F. Teymouri, and L. P. Ovard. 2013. Chemical preconversion: application of low-severity pretreatment chemistries for commoditization of lignocellulosic feedstock. Biofuels 4:323–340.